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14. ABSTRACT
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15. SUBJECT TERMS

Light-emitting triode; light-emitting diode; carrier-injection efficiency; efficiency droop; UV emitters; detection and monitoring of chemical and biological agents

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GaN light-emitting triodes (LETs) for high-efficiency hole injection and for assessment of the physical origin of the efficiency droop

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Abstract

The light-emitting triode (LET) is a three-terminal p-n junction device that accelerates carriers in the lateral direction, i.e. parallel to the p-n junction plane, by means of an electric field between two anodes. The lateral field provides additional energy to carriers thereby allowing them to overcome barriers and increasing the carrier injection efficiency into the active region. LETs were fabricated using a ultraviolet LED structure that has an AlGaN/GaN superlattice in the p-type confinement region for high-conductivity 2 dimensional hole gas. It is shown that both, the current between Anode 1 and the cathode, and the light-output power increase with increasing negative bias to the Anode 2. This is consistent with the expectation that a negative bias to the second anode allows carriers to acquire a high kinetic energy thereby enabling them to overcome the barrier for holes, resulting in high injection efficiency into the active region that lies beyond the barrier. In addition, we have proposed an innovative approach that allows us to investigate the relationship between the hole-injection efficiency and the efficiency droop by using the LET (the efficiency droop is the decrease in efficiency of III-V nitride pn-junction devices with increasing injection current). Our simulation reveals that the electron overflow into the p-type GaN cladding layer, caused by low hole-injection efficiency into the MQW active region, is the origin of the efficiency droop. Therefore, the LET, in which the hole-injection efficiency can be controlled by the bias to the second anode, can be an effective method to investigate the physical origin of the efficiency droop. We believe that our research has been highly successful because it has allowed us to analyze and identify the origin of the efficiency droop in III-V nitride pn junction devices. Since this is known to be a major problem, the resolution of this problem is a major step forward in the development of III-V emitter technology including UV emitter technology.

Note: *The Abstract Section, the Conclusion Section, and the Experimental Section, in particular Section 3B, are completely new, or significant new information has been added. The Introduction Section and Theory Section of this report are similar to our previous ARO report submitted in August 2006.*

1. Introduction

AlGaN-based ultraviolet (UV) light-emitting diodes (LEDs) are attracting much attention for applications such as chemical and biological detection systems, water and air sterilization, and as primary light source for phosphor-based white LEDs.[1~3] Although UV LEDs are already commercially available, highly efficient UV LEDs are still difficult to fabricate. Improvement of the efficiency is one of the most important challenges especially for deep UV LEDs ($\lambda < 340$ nm) which have very low internal quantum efficiency. In AlGaN-based UV LEDs, an electron-blocking layer (EBL) is frequently inserted between the p-type cladding layer and the active region. The EBL has the purpose of preventing electron overflow from the active region, and hence, confining electrons to the active region. **Figure** 1 (a) shows a schematic band diagram of a UV LED with an EBL on a multiple quantum well (MQW) active region. The EBL does not impede hole injection into the active region, if the EBL is heavily p-doped. However, AlGaN with high Al content generally lacks high p-type doping capability which is caused by the high acceptor activation energy of > 200 meV. If the EBL is undoped or low p-doped, it will not only block electrons from escaping the active region but also hinder the injection of holes into the active region by the potential barrier, as shown in the **Figure** 1 (a). The tunneling probability of holes through the EBL is low due to a high potential barrier as well as the heavy mass of holes in GaN ($m_h^* = 0.80 \times m_e$) and AlN ($m_h^* = 3.53 \times m_e$). This limits the hole injection efficiency into the active region, and hence internal quantum efficiency.
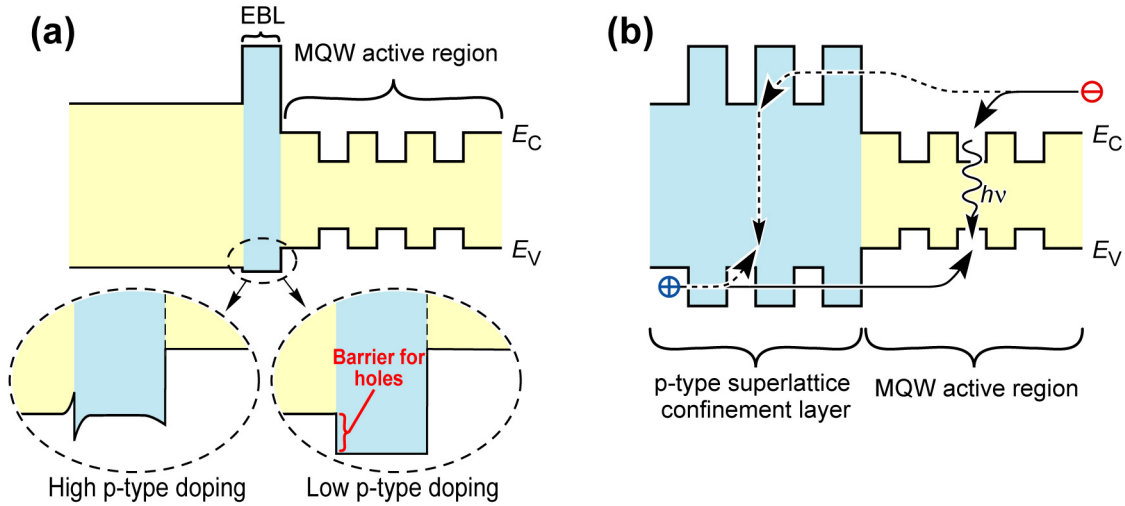

Figure 1: (a) Schematic band diagram of a UV LED with electron-blocking layer (EBL) on multiple quantum well (MQW) active region. (b) Schematic band diagram of a UV LED showing electron and hole transport in light-emitting diode with p-type superlattice confinement region.

In order to overcome the lack of p-type conductivity in bulk $Al_xGa_{1-x}N$ films, Mg doped $Al_xGa_{1-x}N$/GaN superlattices (SLs) have been proposed and demonstrated to have a doping efficiency that is 10 times higher than that of bulk p-type GaN.[4,5] The enhancement of carrier transport has been verified in lateral direction, i. e. parallel to the SLs planes. However, carrier transport along the perpendicular direction through p-n junction, which is required in typical

light-emitting devices, is less efficient than along the lateral direction because most of the holes ionized from the acceptors are localized inside the quantum wells which are clad by potential barriers as high as 100 to 400 meV.[6] The hindrance of carriers in overcoming the barrier results in a low injection efficiency of carriers in the active region, leading to poor internal quantum efficiency of LEDs. *Figure* 1 (b) shows a schematic band diagram of an LED with p-type SLs on top of the MQW active region. A schematic description of electron and hole transport in the LED structure is also shown. Efficient injection of holes into the active region of a LED is required for high radiative efficiency. For inefficient hole injection into the active region, electrons will diffuse through the active region into the p-type confinement layer, where non-radiative recombination is likely.

The light-emitting *triode* (LET) has been motivated by the problem of low injection efficiency in LEDs having a p-type superlattice in the confinement region.[7~9] Schematic sketches of the LED and LET are shown in *Figure* 2(a) and 2(b), respectively. Radiative recombination in active region is strongly required for high-efficiency light-emitting devices. In LEDs, however, non-radiative recombination occurs in p-type confinement region due to an inefficient hole injection over the potential barrier, either by EBL or SLs. The LET is similar to a conventional LED with one important difference: The LET has *three* terminals, two of which are p-type terminals, Anode 1 and Anode 2, and one of which is an n-type terminal, cathode, as shown in Fig 2(b). The fundamental operating principle of the LET is as follows. We assume that the cathode is grounded and the two anodes are both biased at a different level. As a result, a current will flow laterally from one anode to the other anode. In the process, the holes will be accelerated, gain a higher energy, and hence be able to overcome the potential barrier by either EBL or SLs and be injected into the active region more easily as compared to a device with one anode. Thus, the LET structure is a promising new structure with potential advantages for devices that have SLs in the p-type confinement region as well as for UV devices that have an EBL.

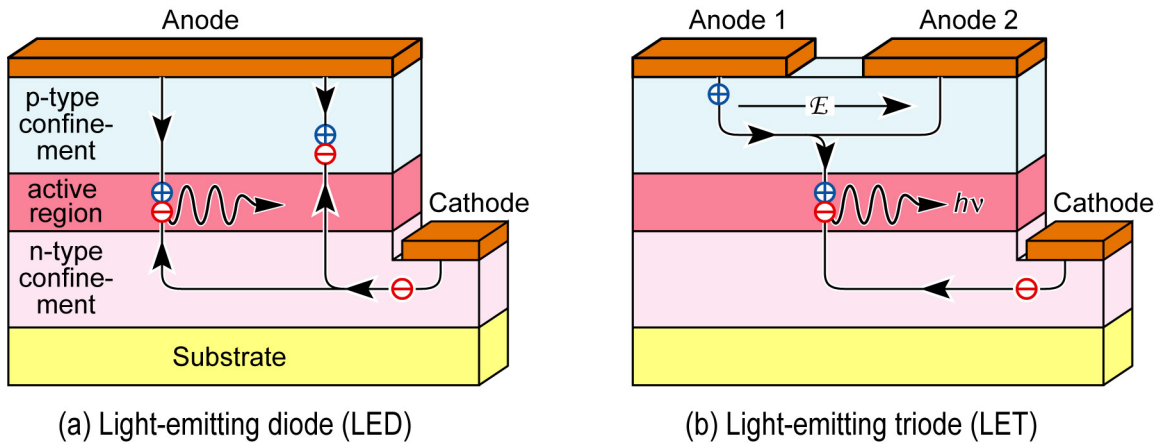(a) Light-emitting diode (LED)   (b) Light-emitting triode (LET)

Figure 2: (a) Light-emitting diode with non-radiative recombination in p-type confinement region. (b) Light-emitting triode with enhanced hole injection into active region and reduced recombination in p-type confinement layer.

2. Theoretical calculation

The carrier temperature can be obtained by equating the energy-gain rate by an electric field to the energy-loss rate by optical phonon scattering. Under steady-state conditions, the two rates are identical, i.e.

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\text{electric field}} = \left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\text{phonon scattering}} \tag{1}$$

with

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\text{electric field}} = e\mathcal{E}\,v = e\mathcal{E}\,\mu\mathcal{E} = e\mu\mathcal{E}^2 \tag{2}$$

and

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t}\right|_{\text{phonon scattering}} = \frac{\frac{3}{2}k(T_c - T)}{\tau_e} \tag{3}$$

where μ is the carrier mobility, $\mathcal{E}$ is the electric field, T is the lattice temperature, T_c is the carrier temperature, and τ_e is the optical phonon scattering time. Inserting Eqs. (2) and (3) into Eq. (1) and solving Eq. (1) for the carrier temperature yields

$$\Delta T_c = T_c - T = e\mu\mathcal{E}^2\tau_e\frac{2}{3k} . \tag{4}$$

Using the Boltzmann distribution, one can calculate the ratio of the carrier concentration at the top of the barrier to the carrier concentration at the bottom of the barrier. This ratio is given by

$$\frac{p_{\text{top}}}{p_{\text{bottom}}} = \exp\left(-\frac{E_{\text{barrier}}}{kT_c}\right) \tag{5}$$

where the height of the barrier is given by E_{barrier}. Assuming that the carrier concentration at the bottom of the barrier is constant, the change in carrier concentration at the top is given by

$$\frac{p_{\text{top}}|_{\text{with field}}}{p_{\text{top}}|_{\text{without field}}} = \exp\left(\frac{E_{\text{barrier}}}{kT} - \frac{E_{\text{barrier}}}{kT_c}\right) . \tag{6}$$

This equation directly gives us the expected improvement in the hole injection into the active region of the LET. **Figure** 3 shows the change in carrier temperature ΔT_c and the ratio of carrier concentration at the top of the barrier $p_{\text{with field}}/p_{\text{without field}}$ as a function of the distance between the two anodes. In the calculation, typical optical phonon scattering time of $\tau_e = 10^{-12}$ s, a p-type GaN hole mobility of 10 cm^2/(V s), a bias voltage of 5 V, a lattice temperature of $T = 300$ K, and a barrier height of $E_{\text{barrier}} = 200$ meV are used. Both ΔT_c and $p_{\text{with field}}/p_{\text{without field}}$ increase with decreasing distance between the two anodes, i.e., with increasing electric field.

Note that ΔT_{c} and $p_{\text{with field}}/p_{\text{without field}}$ increase rapidly at electric fields higher than $\sim 15 \times 10^5$ V/m. For example, one obtains a hole-temperature increase of $\Delta T_{\mathrm{c}} = 7.7$ K, and a corresponding improvement in hole injection by a factor of 1.2 at the distance of $d = 5$ μm, which gives an electric field of 10^6 V/m. At the distance of $d = 1$ μm, i.e. electric field of 5×10^6 V/m, the increase of hole-temperature is as high as $\Delta T_{\mathrm{c}} = 193$ K. This corresponds to an improvement in hole injection over the potential barrier by a factor of 20.3. This is a very encouraging theoretical result that motivates the pursuit of the LET. In addition, this calculation suggests small lateral dimensions between the two anodes in order to get a high electric field that elevates the hole temperature for a reasonable inter-anode bias range. Scaling down the distance between Anode 1 and Anode 2 will afford a reduction in lateral bias. LETs with spiral- and interdigitated-type anodes were designed and fabricated to meet these requirements.
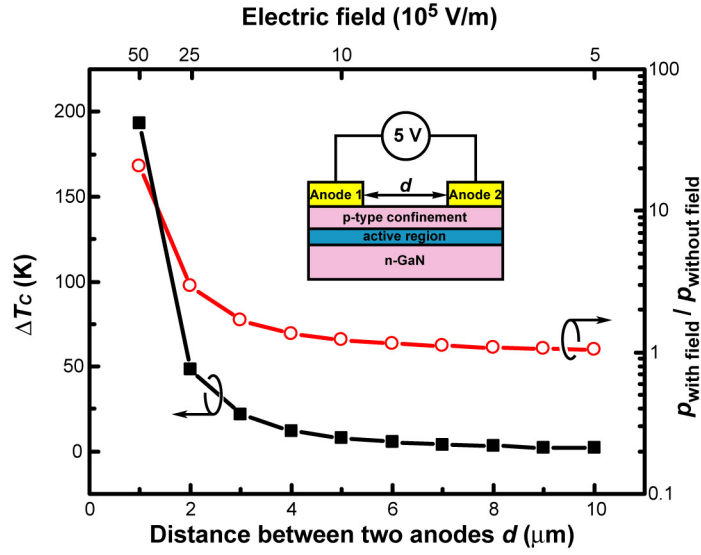

Figure 3: The variation in carrier temperature ΔT_{c} and carrier concentration at the top of the barrier by the bias of 5 V between the two anodes as a function of the distance between the two anodes.

3. Experiments and Results

Section 3A – LETs with high-efficiency hole-injection and light emission

LETs were fabricated on two different UV LED wafers. One is a deep UV LED wafer with peak wavelength of $\lambda_{\text{peak}} = 305$ nm having a p-type $Al_{0.35}Ga_{0.65}N$ EBL. The other is a UV LED wafer with peak wavelength of $\lambda_{\text{peak}} = 400$ nm having an $Al_{0.15}Ga_{0.85}N/GaN$ p-type SL. The 305 nm UV LED structure was grown by metal-organic chemical vapor deposition (MOCVD) on c-plane sapphire substrate and consists of a 1 μm-thick AlN buffer layer, a 3 μm-thick n-type $Al_{0.2}Ga_{0.8}N$ lower cladding layer, a $Al_{0.2}In_{0.03}Ga_{0.77}N/Al_{0.11}In_{0.03}Ga_{0.86}N$ (25/25 Å) double quantum well active region, a 20 nm-thick p-type $Al_{0.35}Ga_{0.65}N$ EBL, and a highly doped p-type GaN contact layer. The 400 nm UV LED structure was grown by MOCVD on c-plane sapphire substrate and consists of a 2 μm-thick undoped GaN buffer layer, an 3 μm-thick n-type GaN lower cladding layer, a 6 period of GaInN/GaN MQW active region, a 20 nm-thick p-type

Al$_{0.15}$Ga$_{0.85}$N EBL, a 13 period of p-type Al$_{0.15}$Ga$_{0.85}$N/GaN (25/50 Å) SLs, and a highly doped p-type GaN contact layer. A 400 nm UV LED wafer without p-type SL was also used for LET fabrication in order to investigate the effect of the SLs on hole injection efficiency.
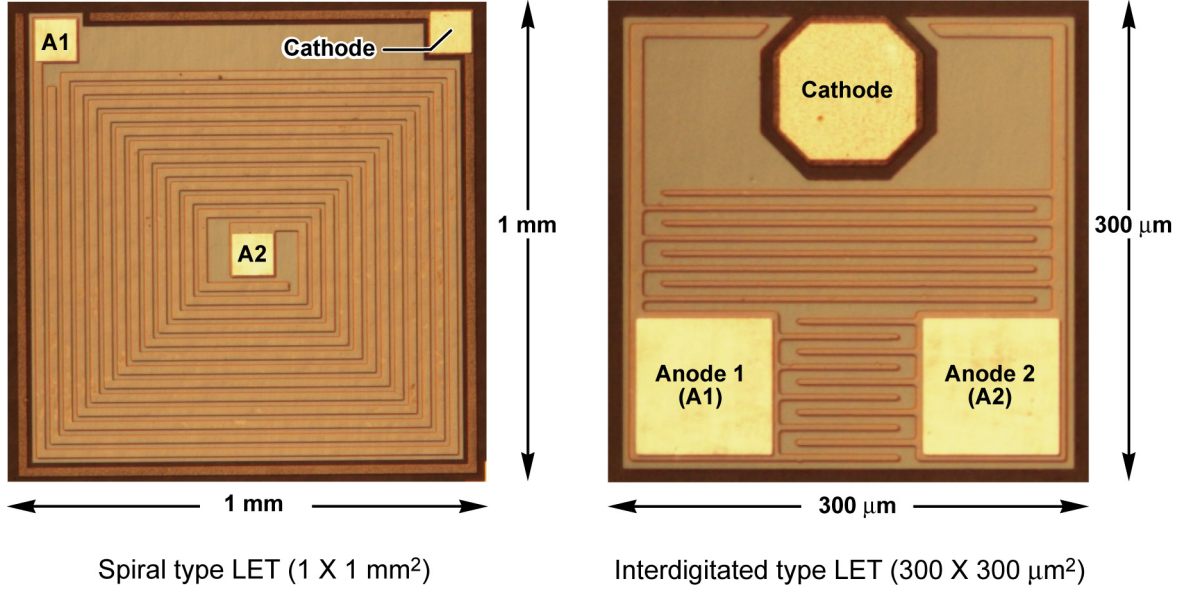

Spiral type LET (1 X 1 mm²)   Interdigitated type LET (300 X 300 μm²)

Figure 4: Optical micrographs of spiral- and interdigitated-type LETs.

LET mesa structures were obtained by standard photolithographic patterning followed by chemically-assisted ion-beam etching using Cl$_2$ and Ar to expose the n-type cladding layer. The n-type ohmic contact was fabricated by electron-beam evaporation of Ti/Al/Ni/Au and annealing at 650 °C for 1 min in N$_2$ ambient. Ni/Au (5/5 nm) ohmic contact layer to p-type GaN was deposited and subsequently annealed at 500 °C in an O$_2$ ambient. Finally, bonding metal was deposited by electron-beam evaporation of Cr/Au (20/500 nm). **Figure** 4 shows optical micrographs of spiral- and interdigitated-type LETs. The chip dimension is 1×1 mm^2 for the spiral-type LET, and 300×300 μm^2 for the interdigitated-type LET. The distance between two anodes is 10 μm for the spiral-type LET, and 4 μm for the interdigitated-type LET.

The electrical properties of the 305 nm UV LETs are shown in **Figure** 5. As a negative bias to Anode 2, V_G, increases, the current between Anode 1 and the cathode increases as well, as shown in **Figure** 5(a). **Figure** 5(b) shows the transconductance, G$_m$= [∂I_{A1-C}/ ∂V_G]$_{VF=constant}$, for different voltages between Anode 1 and cathode, V_F. As the V_G increases negatively, G_m becomes more negative, which is attributed to an enhanced hole injection efficiency over the potential barrier by the Al$_{0.35}$Ga$_{0.65}$N EBL.
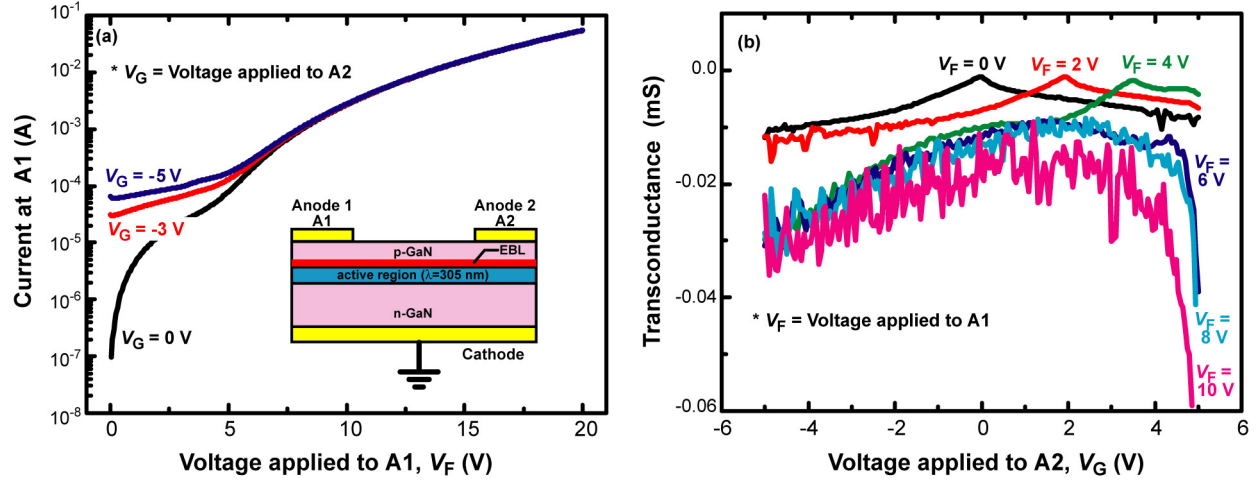
Figure 5: (a) Current-voltage characteristics and (b) transconductance, $G_m = [\partial I_{A1-C}/\partial V_G]_{VF=constant}$, of the 305 nm UV LET.

The electroluminescence intensity from the backsides of the LETs was measured directly on a large-size (10×10 mm^2) Si PIN photodetector. The light-output–versus-current characteristic of the 305 nm UV LETs is shown in **Figure** 6. Inspection of the figure clearly reveals that the light output power depends on the bias to Anode 2, V_G, particularly at small forward current values. As the V_G decreases, both the current through cathode and the light-output power increase. This is consistent with the theoretical consideration that a negative bias to the second anode allows carriers to acquire a high kinetic energy thereby enabling them to overcome the barrier for holes, resulting in high hole injection efficiency into the active region that lies beyond the barrier. Although this result was obtained for a UV LET structure with an EBL, it should be reproducible for LET structures employing SLs for the p-type cladding layer.
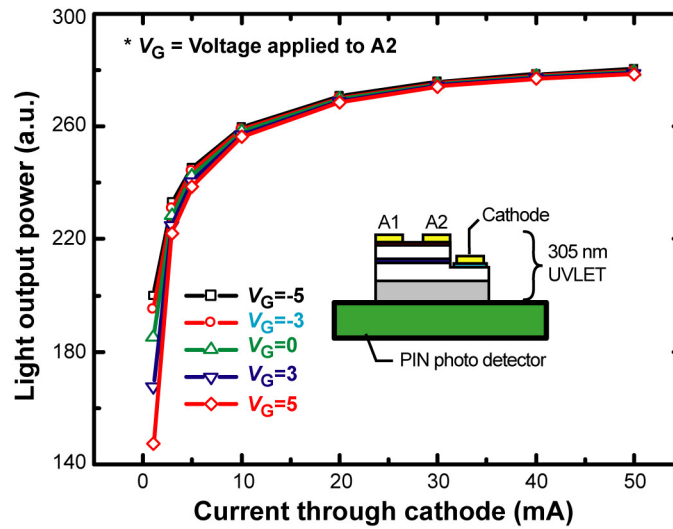

Figure 6: Light-output power–versus-current characteristic of the 305 nm UV LETs. The light-output power from the backside of the LET was measured directly on Si PIN photodetector.

The light-output–versus-current characteristics of the 400 nm UV LETs without SLs and with AlGaN/GaN SLs are shown in *Figure* 7 (a) and (b), respectively. No change in light-output with V_G is observed for 400 nm UV LET without SLs. However, for the 400 nm UV LET with AlGaN/GaN SLs, the light output power depends on the bias to Anode 2, V_G. As the V_G decreases, the light output power increases even though the current through cathode remains constant. This is an important finding and consistent with the expectation that UV LET structure employing SLs as well as employing an EBL showed enhanced light output with increasing negative bias to the additional anode A2. A negative bias to the second anode allows carriers to acquire a high kinetic energy thereby enabling them to overcome the barrier for holes, resulting in high injection efficiency into the active region that lies beyond the barrier. Furthermore, it is worthwhile to note that there is no ambiguity at all with respect to the current that flows through the pn junction. The current measured at the n-type contact must necessarily flow through the pn junction. Therefore, the results unambiguously confirm the validity of the LET concept.
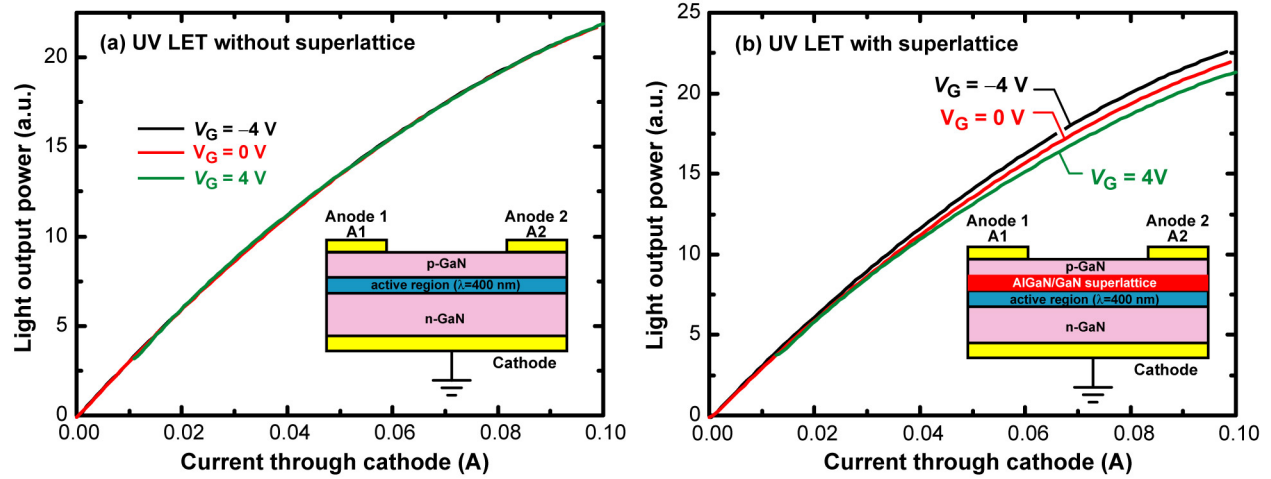

Figure 7: The light-output power–versus-current characteristic of the 400 nm UV LETs (a) without and (b) with AlGaN/GaN SLs.

Section 3B – LETs for assessment of physical origin of efficiency droop

It is a well known and a common finding that the efficiency of III-V nitride pn-junction devices decreases with increasing injection current. This phenomenon is known as ***efficiency droop*** and is shown in *Figure* 8 for UV, blue, and green GaInN devices. The efficiency peaks at low currents and then decreases continuously. Because DC and pulsed measurements (duty cycle of 1%) exhibit the same trend, the efficiency droop is *not* caused by device heating. The efficiency droop is a severe obstacle for injection lasers and high-power solid-state lighting devices. These devices are naturally injected with high current densities, i.e. in an injection-current regime in which the efficiency is much less than its maximum value. This fact represents a strong motivation to understand the cause for the efficiency droop, and, once understood, find ways to overcome this detrimental effect.
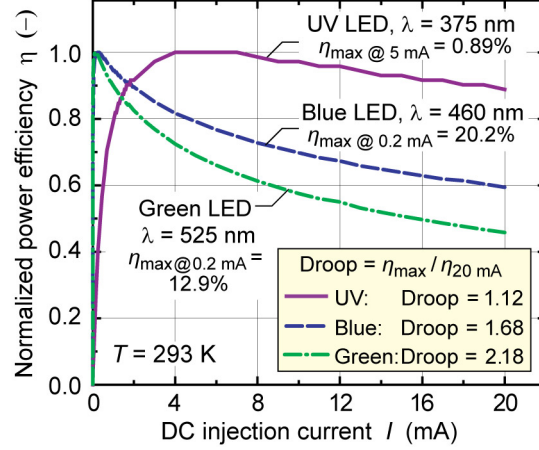
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Figure 8: Measured power efficiency of GaInN LEDs emitting in UV, blue, and green spectral range, as a function of DC injection current.

Carrier loss over the EBL has been identified as one possible mechanism for the efficiency droop occurring at high current densities. By using current transport simulations (using the Crosslight APSYS program in collaboration with Dr. Joachim Piprek of the NUSOD Institute), we have verified that the electron loss over the EBL indeed occurs and that this carrier loss is indeed a very viable hypothesis for the physical origin of the efficiency droop.

An example of a one-dimensional band diagram simulation performed by us is shown in *Figure* 9(a). The simulation takes into account both spontaneous and piezoelectric polarization effects. The band diagram shown is under forward bias conditions, as can be easily verified by the location and spatial dependence of the quasi-Fermi levels. The structure includes a MQW GaInN/GaN active region in which the barrier layers are heavily n-doped with Si. The structure also includes a p-doped AlGaN EBL. Following the EBL is a p-type GaN layer with a free carrier concentration in the 10^{17} cm^{-3} doping range. The top layer is a heavily Mg-doped GaN layer to facilitate the formation of ohmic contacts. The structure shown in *Figure* 9(a) is not an optimized structure and instead is intended to demonstrate the valuable insight that can be deduced from the simulation.

Note that the simulation show that the polarization fields play a major role in the functionality of the EBL. Inspection of *Figure* 9(a) shows that the EBL, as seen by electrons residing in the MQW region, is of triangular shape. For electrons to reach the top p-type GaN layer, they must tunnel through the triangular barrier forming at the MQW side of the EBL. The effectiveness of the EBL is thus reduced by the polarization fields. Consequently, most of the thickness of the EBL has little relevance (particularly the top, p-type end of the EBL) for the blocking of electrons. This deficiency can be alleviated by using a thinner EBL and by increasing the Al content in the EBL.

In addition, our simulations have shown that holes play a very different role than electrons play. Holes, with their inherently low diffusion constant and heavier mass, do not as rapidly diffuse and do not as easily tunnel as electrons do. As a result, the distribution of holes within the MQW structure is quite non-uniform as shown in *Figure* 9(b). Holes predominantly reside in the QW closest to the EBL and do not readily diffuse to QWs farther away from the EBL. Un-populated quantum wells lack optical transparency and thus would need to be photo-excited by waveguided optical modes, in order to reach transparency and ultimately gain. The non-uniform hole population of QWs can be reduced by several methods, for example, increasing hole-

injection efficiency, and reducing the barrier thickness between the QWs or by reducing the number of QWs.
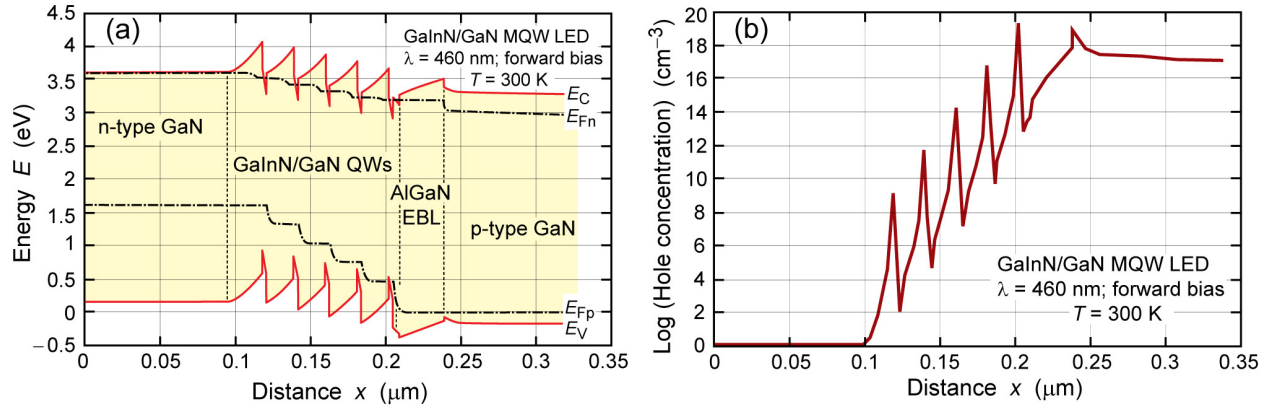

Figure 9: (a) Calculated band diagram of GaInN/GaN LED under forward bias conditions (EBL = electron-blocking layer). (b) Distribution of holes within the MQW structure under forward bias conditions.

As discussed earlier in this report, the electron overflow to the p-cladding layer is identified as a probable mechanism for the efficiency droop occurring at high current densities. It is well understood that holes generally have a low mobility and are well confined by the MQW active region, so that the escape of holes out of the MQW is not a significant issue (for this reason there is no need for a hole-blocking layer, HBL). However, electron loss over the EBL is identified as a significant issue. This gives rise to the question: What causes such a large electron overflow in GaN-based pn-junction devices? The origin of *electron* overflow could be caused by the *low hole-injection efficiency* into the MQW active region. The cause of the low hole injection efficiency is (i) very low hole mobilities in the top layers (and thus the small drift velocity of holes) and (ii) the hindrance of holes by the EBL when injected into the MQW active region.

Here we have pursued an innovative approach that allows us to investigate the relationship between the hole-injection efficiency and the efficiency droop using the LET. The LET enhances hole injection by lateral acceleration of holes, thereby providing additional energy that allows carriers to overcome the barrier(s) formed by the EBL or by a p-type AlGaN/GaN superlattice that is frequently employed to enhance the notoriously difficult p-type doping properties of GaN and AlGaN.

Figure 10(a) shows the simulated electron current as a function of the position of the LED structure shown in *Figure* 9(a). In order to investigate the relationship between hole-injection efficiency and carrier loss over EBL, and hence the efficiency droop, two values of hole mobility are assumed in the simulation, 1 and 10 cm^2/Vs, respectively. The minus sign of the ordinate is merely a consequence of the fact that the electrical current flows in the negative x direction (from right to left). Inspection of *Figure* 10(a) shows that at high injection conditions, when the current density is high, 38.7 A/cm^2, a significant fraction of the electron current leaks out of the MQW active region into the top p-type GaN layer. As the hole mobility decreases, the electron leakage current increases. ~ 60% of the electron current leaks out of the MQW active region into the top p-type GaN layer for the LED with hole mobility of 10 cm^2/Vs. For the LED with hole mobility

of $1~\text{cm}^2/\text{Vs}$, more than 85% of the electron current leaks out of the active region. Our simulations reveal that the electron loss over the EBL indeed occurs significantly, and that this carrier loss is indeed a very viable hypothesis for the physical origin of the efficiency droop.

Figure 10(a) also reveals that the current density decreases only slightly in the top p-type GaN layer which means that most carriers leaking out of the active region reach the top contact layer where the carriers ultimately recombine non-radiatively by surface recombination. We have also performed calculations of the hole current (not shown). These calculations reveal that the hole current is reduced to virtually zero when reaching the second quantum well. This clearly indicates that hole diffusion beyond the MQW active regions not a problem. Thus no hole-blocking layer (HBL) is needed.
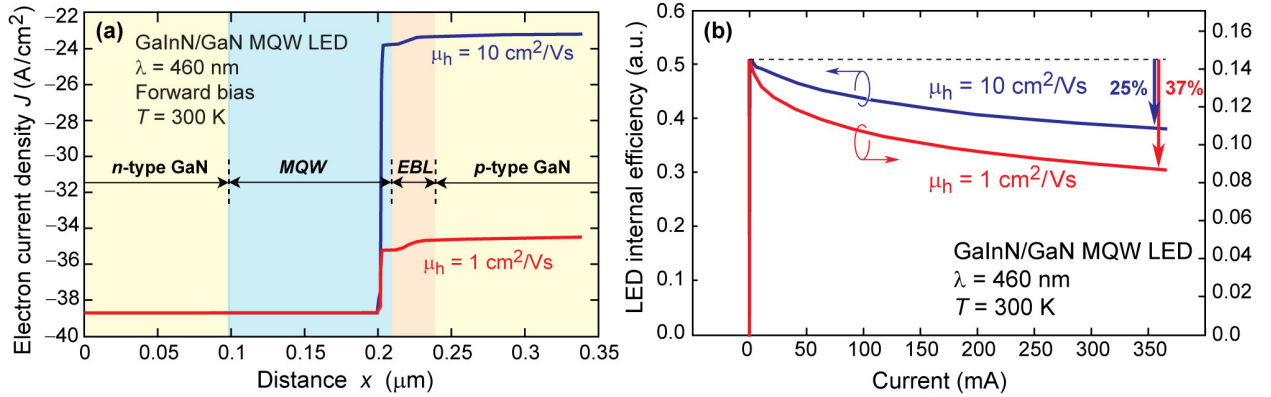

Figure 10: (a) Electron current in pn-junction LED as a function of distance. Note that a significant fraction of the current flows across the EBL. (b) Simulated power efficiency of GaInN LEDs emitting 460 nm with hole mobilities of 1 and 10 cm^2/Vs, as a function of DC injection current.

Figure 10(b) shows the simulated internal efficiency of the LED with hole mobilities of $1~\text{cm}^2/\text{Vs}$ and $10~\text{cm}^2/\text{Vs}$. The efficiency peaks at very low currents and then decreases continuously showing efficiency droop. The LED structure with hole mobility of $10~\text{cm}^2/\text{Vs}$ shows 25% efficiency droop. When the hole mobility decreases to $1~\text{cm}^2/\text{Vs}$, the efficiency droop significantly increases to 37%. This result supports our innovative LET approach that allows us to investigate the physical origin of efficiency droop using the LET. The low hole-injection efficiency into active region is likely to be a major factor in non-uniform distribution of holes in the MQW, as shown in *Figure* 9(b). The dependency of the hole-injection efficiency on efficiency droop investigated by using LET, in which the hole-injection efficiency can be controlled by the bias to the second anode, will give us critical confirmation of the physical origin of the efficiency droop.

Conclusions

In conclusion, a new type of light-emitting device, the light-emitting triode (LET), is demonstrated to have enhanced hole injection efficiency. Theoretical calculations reveal that the lateral electric field of 5×10^6 V/m provides an additional energy to holes increasing their temperature by $\Delta T_c = 193$ K, thereby allowing them to overcome potential barriers by either superlattices or electron-blocking layer. This leads to the improvement of hole injection efficiency into the active region by a factor of 20.3. UV LETs (λ_{peak} = 305 nm) having p-type $Al_{0.35}Ga_{0.65}N$ EBL and UV LETs (λ_{peak} = 400 nm) having AlGaN/GaN SLs, are fabricated. It is experimentally shown that the light-output power of LETs increases with increasing negative bias to the additional anode. This is consistent with the theoretical consideration that a negative bias to the second anode allows carriers to acquire a high kinetic energy thereby enabling them to overcome the barrier for holes, resulting in high hole injection efficiency into the active region that lies beyond the barrier. Furthermore, we have proposed an innovative approach that allows us to investigate the relationship between the hole-injection efficiency and the efficiency droop using the LET. Our simulations reveal that the electron overflow to the p-cladding layer due to low hole-injection efficiency into the MQW active region is identified as the very likely mechanism for the efficiency droop. Therefore, the LET, in which the hole-injection efficiency can be controlled by the bias to the second anode, is an effective method to confirm the physical origin of the efficiency droop.

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